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Loading history and structure of fracture of material

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Abstract

The bearing capacity of the structured materials and features of their fracture depend on local reaction of elements of structure on loading history. The initial structure of material can be modified in the course of prefracture at the initial stage of loading such that at further deformation, including deformation with the changed ratio of loadings on axes, this induced structure determines the scenario of fracture of material and its strength. The effective strength of heterogeneous materials and scenarios of their fracture are influenced by the level of the intermediate main stress. At compression of a cracked body lack of significant reaction to stresses along the sliding plane is characteristic for initial microcracks (areas of sliding). In a porous body such effect is absent. Therefore at tests with the proportional mode of loading according to the Karman or Böker schemes the effective measured strength can differ.

To estimate an influence of a type of initial structural elements – pores and microcracks - on a final phase of fracture at uniaxial compression within a plane problem, an approach based on their equivalence to action of some concentrated forces is used. If the main crack is formed by joining a system of microcracks – the sliding areas, the movement on which causes the wedging forces, then weakening of the action in the process of the main crack growth is small. In case of a porous structure an influence of pores, remote from the crack tip, on the effective stress intensity factor K_I in the process of crack sizes increasing weakens much faster. Therefore in a porous body development of echelons of rather short cracks joining small number of pores (N ~ 2-3) is energetically preferable, while occurring of the main cracks is characteristic for a cracked body at a final stage of fracture at compression. For a body with microcracks in which after coalescence of cracks from two and more concentrators the stress intensity factors for the formed defect become larger than it was at the moment of microcracks coalescence, the choice of the fracture scenario – development of the main fault occurs at the initial stage of fracture.

In the porous body, forming the cracks with an influence of pores, favorable conditions for initiation of fracture in the new source of fracture at the small size of cracks are only created near the crack tips. The induced structure of fracture arising at partial unloading also influences the fracture mechanism at the subsequent loading. Development of a system of the feathering of cracks in the vicinity of the main fault also belongs to such structures. The last can be used as a method for the main crack arresting.

Keywords: crack, structure, compression, porous body, cracked body, fracture, loading, history

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1. Introduction

Effective strength of heterogeneous materials and scenarios of their fracture can react variously to a change of loading parameters. It is possible to separate the publications in which an influence of macrotexture of a medium (layered or block wise) on the bearing capacity of the medium is analyzed at various variants of loading (Vlasov (2007), Tang, Liang, Zhang et al. (2008)). Another direction of studies is related to consecutive creation of fracture scenarios on the basis of an analysis of activity of basic elements of a material structure (pores, microcracks, inclusions) under the influence of mechanical loadings in rocks and structural materials, and also on the description of the relevant fracture mechanisms (Brace, Bombolakis (1963), Hoek, Bieniawski (1965), Goldstein, Ladygin, Osipenko (1974), Lajtai (1975), Ashby, Hallam (1986), Germanovich, Dyskin, Tsyrulnikov (1993), Plaisted, Amirkhizi, Nemat-Nasser (2006)). In some cases fracture development in the structured media is accompanied by formation of ordered systems of violations (Goldstein, Osipenko (1978)), and also scale effects are observed (Hoek, Bieniawski (1965), Bazant, Planas (1998)). Among the questions drawing attention one can mention an influence of a type of elements of a material structure on its strength at a multi-axial stress state, a change of volume at deformation and fracture, a scenario of fracture, including formation of the ordered violations. Below development of microcracks in the vicinity of a pores and microcracks (areas of sliding) at the external compression loadings is considered in the course of the publications (Goldstein, Ladygin, Osipenko (1974), Goldstein, Osipenko (1978), Goldstein, Osipenko (2015)).

2. An influence of an intermediate stress

If in a body with evenly distributed microcracks of various orientations the smallest and intermediate main stresses are equal, initial defects with orientation in space (a corner to an axis of the greatest compression) closed to optimum are essential. At increase of the intermediate stress, a part of sliding areas is blocked. At the same time the ratio of effective strength at bulk compression in the case when the intermediate stress corresponds to a condition of blocking of initial defects and in the variant when it is close to the minimum main stress $\left(\sigma_y = \sigma_x\right)$, with other things being equal, is equal to $\left(\sigma^*_{max}/\sigma^*_0\right) \approx 1.23$ (Goldstein, Osipenko (2015)). Addressing a porous body, we will note that in the considered range of loading conditions for such body there are no situations of microcracks blocking. At three-axial compression an increase of the intermediate main stress, in cracked structure leads to a slight increase of its bearing capacity due to arrest of defects of some orientations. For a porous body, on the other hand, it is characteristic the termination of cracks growth on pores boundaries since the level of the tensile stresses sharply decreases at the pore contour that practically means a transition of fracture to another, smaller scale of material structure .

One of the signs of fracture development in the structured medium is the effect of a change of volume (dilatation). For microcracked structure the increase in volume related to the growth of cracks occurs right after their initiation (Germanovich, Dyskin (2000)). Contrary, the effect of a volume decrease at the initial stage of fracture is inherent to a porous body because of deformation of a porous space. This circumstance allows to separate a deformation sign of a pore space participation in the fracture scenario (Goldstein, Osipenko (2015)). At fracture initiation a change of volume of the medium also occurs differently. If for a medium with microcracks an increase in volume after cracks initiation on boundaries of the sliding areas is characteristic, in a porous body volume reduction due to deformation of a pores prevails at the beginning of the process at uniaxial compression. Further, in the process of cracks growth volume grows. Nonmonotone volume change can serve as an indicator of the type of structure which determines fracture progress. The described situation is characteristic at prevalence of compression, it changes at change of a stress state. In particular, a change of volume of a pore space doesn't occur at the pure shear stresses. Its variations are only related to the cracks growth.

3. Characteristic options of the main structures of fractures development

Characteristic distinction between fracture parameters of media with various structures is seen in features of development of the main cracks which are formed at joining of the microcracks growing in vicinities of structural elements.

Remaining within the framework of a plane problem, let us consider an influence of a type of initial elements of structure – pores and microcracks - on the scenario of fracture at uniaxial compression. For further estimates we will use approximate representations (Fairhurst, Cook (1966), Germanovich, Dyskin (2000), Goldstein, Osipenko (1999)) about equivalence of an action from microcracks on neighboring material to the action of some concentrated loads P on the surfaces of the cracks growing in vicinities of these concentrators. In case of pores such approach can be accepted for the state near the limit equilibrium at coalescence of the cracks growing in the pores vicinities. The effective concentrated force at the same time can be estimated, equating stress intensity factors for the fixed crack length in cases of pores and the concentrated force

$$\frac{P}{\sqrt{\pi L}} \approx -\frac{1.1\sigma_z\sqrt{\pi(L-a)}}{(L/a)^{3.3}} \tag{1}$$

or

$$P \approx -1.1\sigma_Z \pi\sqrt{L(L-a)}\Big/(L/a)^{3.3}\ , \tag{2}$$

where σ_Z is the compressive stress, a is the pores radius, $2L$ is the distance between centers of pores.

For a single microcrack with crack surfaces being in contact with friction (Dyskin, Salganik (1987)

$$K_1 \approx C\frac{2\sigma_\infty a}{\sqrt{\pi\ell}} sin^2\alpha\cos\alpha \tag{3}$$

$$C = F(f_{fr}) \sim 1$$

where F is determined by the friction coefficient, α is a angle between the plane of a crack and an axis of compression

The example of comparison of crack growth conditions in the vicinity of a single pore and microcrack is given in fig.1. Data for the pores are taken from (Murakami (1990)). It is possible to see that, in the interesting range of cracks lengths ($\ell / R > 1$), an influence of a single pore on the stress intensity factors K_1 in the tip of the feathering microcrack at the crack size increase decreases much faster, than an influence of sliding areas in a cracked body.

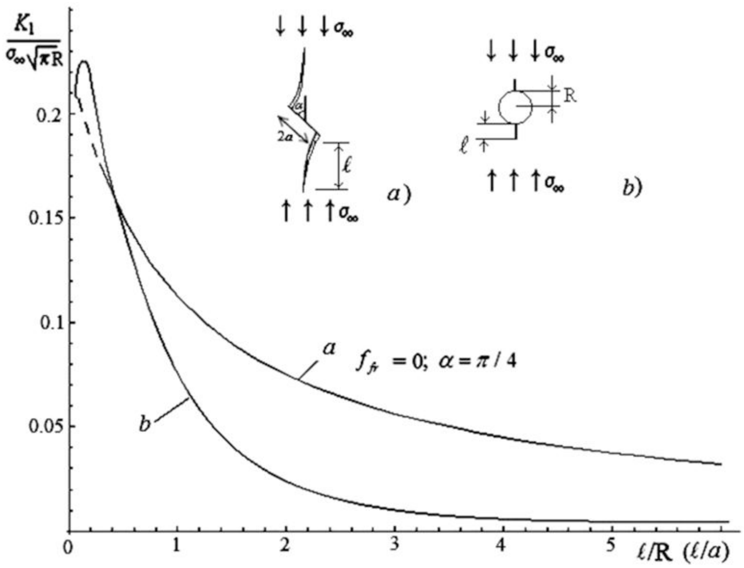

Fig.1. Comparison of crack growth conditions in the vicinity of a single pore and microcrack

In the process of separate cracks coalescence the main cracks are formed. An action of initial concentrators on their surfaces partially remains. This action can be modeled by a periodic system of loads (fig.2). Note, that ability of the concentrators which are included in the main cracks to keep force action on crack surfaces depends on the nature of the concentrators.

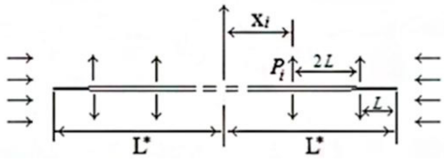

Fig.2. The scheme of the main crack joining several concentrators

We will illustrate this effect, comparing a contribution of individual concentrators to stress intensity factors in the tip of the main crack as it grows (fig.3). At the same time we will assume that concentrators are located periodically at distance 2L from each other.

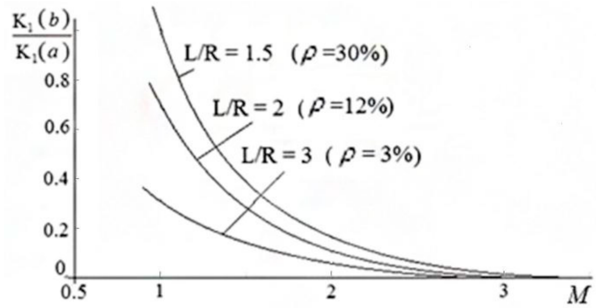

Fig.3. The ratio of stress of intensity factors for feathering cracks for a pores (b) and microcracks (a) in a function of relative distance of this concentrator from the tip of the main crack; M – number of the intervals 2L separating the concentrator from the crack tip

In brackets it is given an estimate of the effective porosity at this ratio of distance between the pores to the pore radius. It is possible to see that an influence of pores weakens faster than in case of sliding areas as a distance from the concentrator to the tip of the main crack increases multiply to the average distance between the concentrators. This distinction increases with increasing the distance between the concentrators (falling of the effective porosity ρ) (fig.3). Thus, it is possible to note that pores and sliding areas (microcracks) as a part of the main crack at compression in the direction of the main crack differently influence on the resulting stress intensity factors in the cracks tip. In a porous body an influence of only several pores nearest to the crack tip is essential. While in a cracked body an influence of larger amount of sliding areas remains to be essential.

To estimate possible consequences of these features of a structural elements influence on the fracture scenario let us consider a model problem on a crack with surfaces being loaded by the concentrated loads limiting an influence of individual concentrators. The stress intensity factors in the tip of the main cracks uniting N defects in elastic-brittle approach are determined as the sum of contributions of these defects. The performed estimates show that if the main crack is formed by a system of the joined pores, then the main crack growth can be modeled by a situation in which a force action is only caused by the pores nearest to the crack tips. It is accompanied by loss of force influences in a middle part of the main crack. In case of wing cracks such effect is absent. Therefore, it is possible to consider that in the limit variant the system of identical forces, is uniformly distributed on length of a main crack through intervals which size is close to an average distance between sliding areas. We will consider these situations by turn.

If the loading is created by a system of N concentrated forces, symmetric relative to the crack axis, (fig.2), an estimate of the stress intensity factor can be obtained by a transformation of the formula for a single load on crack surfaces (Cherepanov (1974)).

$$K_I(n) = \sum_1^n \frac{P_i\left(L^* + x_i\right)}{\sqrt{\pi L^*\left(\left(L^*\right)^2 - x_i^2\right)}}, \quad P_i \approx P_{ef}, \quad K_I(n) = -\frac{1.1\sigma_1\sqrt{\pi}\sqrt{(L-a)}}{\sqrt{N}\left(L/a\right)^{3.3}}\sum_1^n \sqrt{\frac{L^* + x_i}{L^* - x_i}} \tag{4}$$

where L^* – total size of the main crack, $L^* = NL$, n – number of the elements included in the main crack, x_i – distance of a point of application of the load P_i from the center of a crack.

The results of calculations of the stress intensity factors in relation to that for a crack with a single pair of concentrated forces, when the crack is lengthen due to joining to it of new elements for the specified variants are given in fig.4. For a crack in which the system of identical forces is distributed on the crack length through equal intervals (type 1) the ratio of the stress intensity factors increases in the process of crack length growth and growth of the number of concentrators included in it (fig.4, curve 1). In case of the concentrated loads action only within the fixed distance from the ends of a crack at small amount of the included elements (type 2), (figs. 4, curve 2), in the process of crack length increase this ratio at first increases a little and then asymptotically decreases (for the crack supported by two pairs of forces on the ends of a crack $\left(K_1(n)/K_1(n=1)\right)_{\max} \approx 1.63$ if only two elements are included in the main crack (N=2-3)). In that and in other cases for fracture supporting it is necessary to provide smaller external loads, than for its initiation (if the initiation conditions are related to coalescence of two cracks growing from the adjacent elements of a structure ($K_1(n)/K_1(n=1) > 1$)).

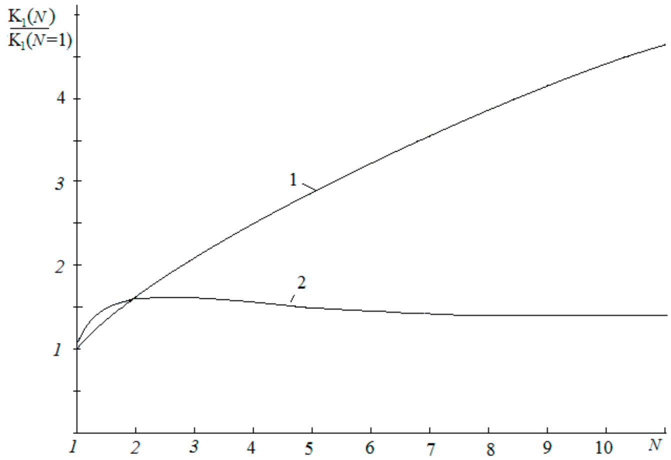

Fig.4 Ratio of the stress intensity factors for the main crack and for a crack with the single concentrator (pair of concentrated forces) for two types of the loads distribution

Such variations of the stress intensity factors allow concluding, in particular, that the compressive strength of the material relating to type 1 more essentially depends on existence of the initial violations equivalent to the main cracks of small length. For instance, in the presence of the initial violation corresponding to the crack uniting 4 elements, the ratio is equal ~ 2.5 and it increases at a crack length increase. At attaining of the limit equilibrium such crack starts to extend catastrophically. Since in the considered variant of elastic-brittle fracture there is a linear interrelation between the limit stresses and K_1, it means that the limit stresses of external compression (strength) of the system, containing such defect in an initial state, decreases by 2.5 times at uniaxial compression.

Another behavior is characteristic for the medium of type 2 with inclusion of active elements only near tips of a crack. The largest value of the ratio is observed at N=2-3. Presence of an initial defect of the larger size isn't the reason of its catastrophic growth at loading. The system will seek to be limited to the cracks of the optimum size containing 2-3 elements. Within such representations it is possible to connect distinction of structure and the registered features of the fracture scenario. So, for a system of type 1 with active influence of all elements through the crack length at uniaxial compression it is possible to expect development of single main cracks without noticeable acts of multiple prefracture, and also occurring of a scale effect of strength since the probability of presence of larger initial defects in the loaded volume increases with the volume increase. Such scenario of fracture is preferable for microcracked media. In case of type 2 media, in particular porous ones, development of the main cracks is complicated. The prefracture processes forming a system of small cracks are of great importance. Such systems of cracks in the form of echelons and echelonlike structures were analyzed in (Goldstein, Osipenko (2010)). Let us consider the conditions of initiation of multiple ordered fractures in the vicinity of the main crack formed according to the described scenarios at compression. In the vicinity of a crack in the area with the characteristic size close to the size of the crack supported by an internal thrust caused by the concentrators, material is compressed and initiation of fracture is complicated. On the other hand, presence of additional tension in the vicinity of crack tips increases a possibility of fracture.

Compare the conditions of the limit equilibrium of the main crack and conditions of fracture initiation in its vicinities, necessary for development of an echelon structure. We will be interested in change of stresses in the vicinity of the tip of the crack growing in the quasistatic regime. In the case of the limit equilibrium at $K_I = K_{IC}$ in the main crack tip, it is possible to estimate stresses in its vicinities using slowly decreasing asymptotics (Cherepanov (1974))

$$\Delta\sigma \approx mK_{IC} \Big/ \sqrt{2\pi s} \ , \tag{5}$$

where s – distance to the crack tip. *m*~1 for a zone on the crack extension, m~1.3 for the most dangerous direction (θ~60^0).

We will choose the area remote from the tip of the main crack on a distance of an order of the crack size. Such ratio is characteristic for the ordered structures of fracture $s \approx L^* \approx NL$.

This is one of asymptotic situations. It is obvious that at closer location of the fracture nucleus the conditions of its initiation are facilitated. We will assume that a necessary condition of initiation of an echelon is the condition of coalescence of cracks growing from two adjacent concentrators in the vicinity of the main crack under the action of stresses caused by external forces and perturbation $\Delta\sigma$. Stresses $\Delta\sigma$ are considered uniform on the scale of area of the action. The condition of the limit equilibrium in the new nucleus of fracture looks as follows

$$K_I = P_{ef} \Big/ \sqrt{\pi L} + \Delta\sigma\sqrt{\pi L} \ , \quad K_I = K_{IC} \tag{6}$$

The first term corresponds to a contribution of the external uniform stress field, the second – an addition influence of the perturbation. In a condition of the limit equilibrium of a system the main crack – the new nucleus of fracture we will assume that the effective concentrated loading in the nucleus of fracture is proportional to the ratio of stress intensity factors in the tip of the single crack and main crack

$$P_{ef} = P_{(N=1)} \frac{K_{I(N=1)}}{K_{I(N)}} = K_{IC}\sqrt{\pi L}\, \frac{K_{I(N=1)}}{K_{I(N)}} \tag{7}$$

Comparing (7) to the condition of the limit equilibrium of the main crack

$$K_{1(N)} = K_{1C} \, , \tag{8}$$

we obtain from Eqs (5) - (8) the condition of initiation of coalescence of concentrators in the new nucleus in vicinities of the main crack

$$\frac{K_{I(N=1)}}{K_{I(N)}} + \frac{m\sqrt{L}}{\sqrt{2N}} \ge 1 \tag{9}$$

Let us compare the conditions of fracture initiation on the crack extension and on the dangerous direction (initiation of an echelon of cracks) for a medium with layered texture and active elements of a structure being at the interfaces (*h* is the layer thickness). Compression acts along the layers. The results of comparison for initial defects, equivalent to a fault containing N^* active elements of the structure, are given in Fig.5. The ratio of the initiation conditions according to inequality (9) is characterized by the parameter *F*

$$F = \left(\frac{K_{I(N^*=1)}}{K_{I(N^*)}} + \frac{1.3\sqrt{L}}{\sqrt{2s}} \right) \Bigg/ \left(\frac{K_{I(N^*=1)}}{K_{I(N^*)}} + \frac{1}{\sqrt{2}} \right); s \approx h / cos 60^0$$

The ratio $K_{I(N=1)} / K_{I(N)}$ was used according to Eq. (4) (Fig.4). One can see that initiation of fracture in the adjacent layer is preferable at (h/L) <4. The result is weakly dependent on the size of an initial defect.

Let us consider fracture kinematics. It is known that if the stress intensity factor in the crack tip increases on each following step at the crack length increment, the crack is unstable and its dynamic propagation occurs. Owing to the effects of inertia in this case nucleation of fracture sources in its vicinities doesn't happen. This is fairly for rather high crack speeds (but smaller, than the speed of the Rayleigh waves in the medium). For a medium with layered texture and porous or cracked structure, the acts of pre-fracture – coalescence of two elements in vicinities of the defect in adjacent layers can occur before attaining the critical state of the defect, if the relative thickness of a layer is less than the size of 4 concentrators. If the size of the initial defect exceeds the size of 4 concentrators, then the limit equilibrium of the defect (crack of larger size) occurs earlier. The defect transition in an unstable state and its dynamic propagation arrest the growth of a secondary source of fracture.

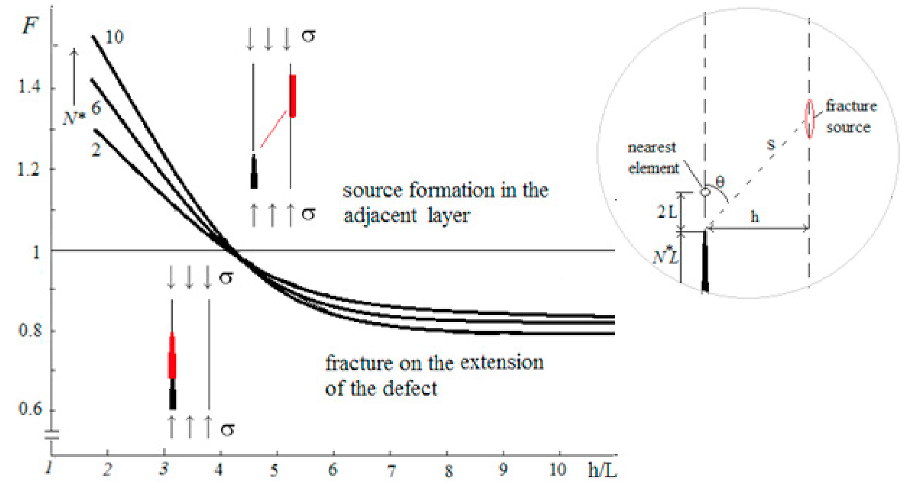

Fig.5. Comparison of the conditions of fracture source initiation (coalescence of elements of the structure) in a vicinity of the initial defect on the extension of the defect or in the adjacent layer

Thus, tendency of the structured material to formation of the ordered systems of cracks or to development of single main cracks at compression is related to activity of the structural elements involved in the growing crack. Modeling of such situation by a periodic system of forces acting on the crack surfaces enabled to separate two characteristic asymptotic variants. If activity of structural elements within the crack is remained in the process of crack growth, i.e. values of forces on crack surfaces imitating this activity are remained, then the stress intensity factors in its tips corresponding to the moment of the limit equilibrium monotonously increases with the crack growth. This variant is close to the process of the main crack growth in the cracked medium. For another case in which activity of elements in the central part of a crack is weakened, as in a porous body, the stress intensity factors in its tips change not monotonously. In particular, if only the nearest to the crack end zones elements are active then their maximum is attained at coalescence of 2-3 elements at uniaxial compression.

Comparison of the conditions of the limit equilibrium of a growing main crack and the limit equilibrium state at joining of two adjacent elements of the structure under the action of external compression and perturbation of the stress state cause by the main crack in a layered medium shows that the ability of a medium to formation of an ordered system – echelon of faults under the uni-axial compression depends on the texture parameters. In particular, in the case of a layered medium – on the relative layers thickness. External tension in the direction transverse to the compression axis strengthens this tendency, compression restricts the sizes of the main crack and increases the ability to formation of crack systems.

External tension in the direction transverse to an axis of compression strengthens this tendency. Compression restricts the sizes of the main crack and increases the tendency to formation of systems of small cracks.

The situation can be changed if in the course of loading to turn an axis of loading after initiation of microcracks. A turn of a porous body on an angle ~ 45^0 can cause transformation of the microcracks which have appeared earlier to areas of sliding. Therefore a tendency to development of the main cracks is gained at compression.

The induced structure arising at partial unloading also influences the fracture mechanism at the subsequent loading. Development of a system of feathering cracks in the vicinity of the main fault also belongs to such structures (Goldstein, Osipenko (2012)). The last can be used as method of arresting of the main cracks by changing the loading direction.

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